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This project, funded for 2.5 years, focused on the modeling of high power femtosecond pulse propagation in air. The work has been very successful and has received a broad exposure amongst academic, industry and DOD communities. Potential applications abound for light strings and the RF electromagnetic pulses emitted from plasma channels generated by these light strings. A number of papers have been published in the literature and others are submitted or in preparation.

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# Final Report
## December 1 2001 to November 30, 2002
## F49620-00-1-0312

# High Power Femtosecond Laser Light Strings

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This project, funded for 2.5 years, focused on the modelling of high power femtosecond pulse propagation in air. The work has been very successful and has received a broad exposure amongst academic, industry and DOD communities. Potential applications abound for light strings and the RF electromagnetic pulses emitted from plasma channels generated by these light strings. A number of papers have been published in the literature and others are submitted or in preparation. Invited papers were presented at the Annual Optical Society of America meeting in Orlando (October 2002), at the Directed Energy 2001 Workshop at Kirtland AFB, at the international "Ultrafast Nonlinear Optics and Semiconductor Lasers" workshop held in Cork, Ireland from September 5-8, 2001, at the "International Symposium on Ultrafast Intense Laser Science" to be held in Quebec City, Canada from October 4-6, 2001, and at the LPHYS2000 international conference in Bordeaux, France in July, 2000.

A subcontract was awarded to Professor J.-C. Diels at the University of New Mexico as partial support his experimental work on UV generated light strings. Lite Cycles of Tucson, who were supported on a small subcontract, provided vital support and connections to potential DOD applications. The collaboration between ACMS and these two groups led to the winning of a Phase I STTR from ARO on UV light string generation. A Phase II STTR contract was recently awarded to Lite Cycles and Diels to build a UV source.

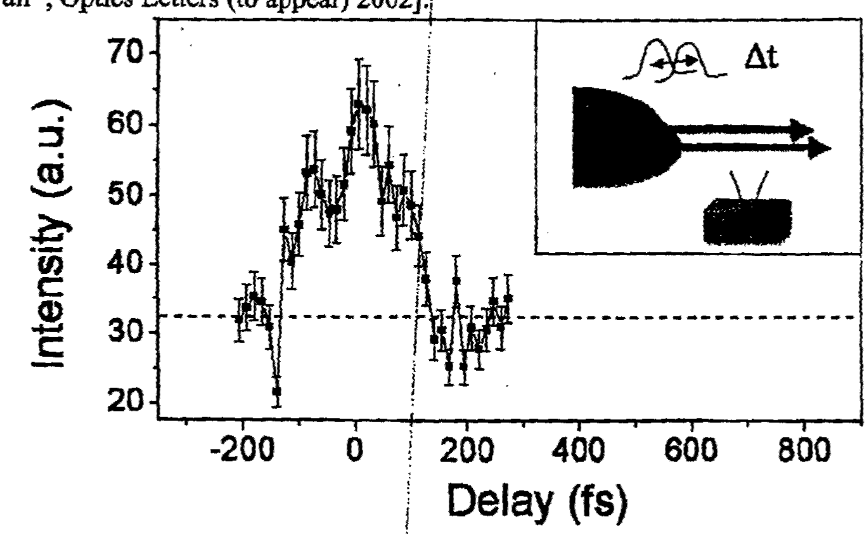
Our work and that of other groups in this field has captured the attention of various DOD groups and James Murray, of Lite Cycles in Tucson, represented our effort at a DARPA meeting in Washington in June, 2002 and a JASONS meeting at La Jolla in July, 2001. Drs. Barry Hogge (AFRL) and Vern Schlie (AFRL) have been actively involved in representing our work to the DOD community. A number of topical articles appeared in the August 2001 issue of Physics Today and the July 2001 issue of Physics World.

The project supported two postdoctoral fellows (M. Kolesik and C.C. Cheng) partime at Arizona and a graduate student in the group of Professor J.-C. Diels at the University of New Mexico.

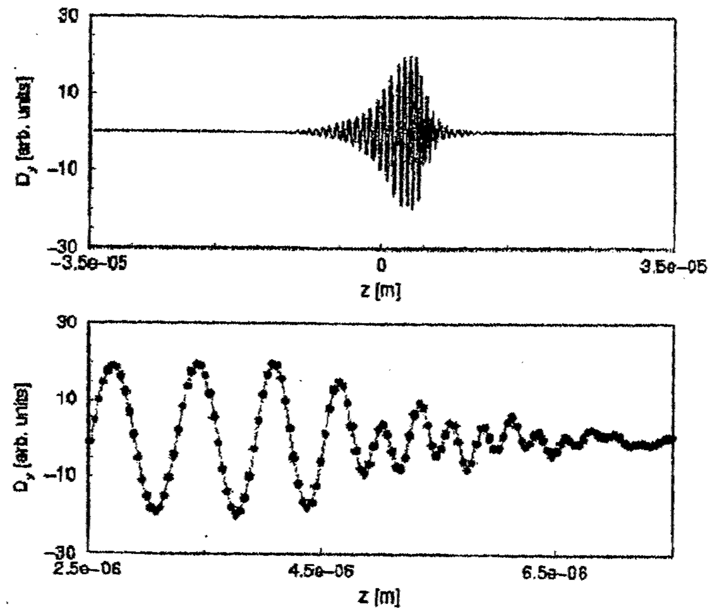
Our existing adaptive mesh refinement schemes for both the scalar and vector propagation problems highlighted some shortcomings and technical difficulties in tracking extreme nonlinear optical compression of the pulse and gradients in the generated plasma along the pulse direction. Although the transverse waist of the pulse is limited to 80-100μ by plasma self-limiting, extreme spectral super-broadening along the pulse direction stretches the validity of the 3D NLS envelope description, even with correction terms included. Unfortunately correction terms appear to be added in a somewhat ad hoc fashion in the literature leading to further confusion in physical interpretation.

Our collaboration with James Murray of Lite Cycles Inc.,Tucson continues to focus on the obscurant penetration problem and LIDAR applications. Professor M. Brio leads this effort with support from a postdoctoral fellow, Armis Zakharian. We have preliminary results on full vector Maxwell solutions to the problem of scattering of few cycle femtosecond pulses by a dielectric disk and we are relating these results, for linear propagation, to the classical Mie scattering formulas. We have been working with the group of J.-C. Diels at the University of New Mexico on comparing our simulation results to experiments in the UV. This work has led to better measurements of fundamental material constants that are critical to building predictive simulation codes. Professor E.M. Wright of the Optical Sciences Center leads this interaction.

A paper on our prediction of the highly transient emission of a many kV/m EMP nanosecond duration pulse from the generated plasma channel was published in Physical Review Letters in 2001. This paper also anticipated the possibility that multiple plasma channels left in the wake of individual chaotic light strings, might emit a coherent RF burst with an $N^2$ enhancement of intensity. A recent paper, in Optics Letters, provides direct experimental evidence for such an enhancement effect [Tzortzakis et al., "Coherent sub THz radiation from femtosecond infrared filaments in air", Optics Letters (to appear) 2002].




The figure above shows the experimental data where a factor of 4 enhancement in the RF emission from two nearby plasma channels is observed when the light strings overlap.

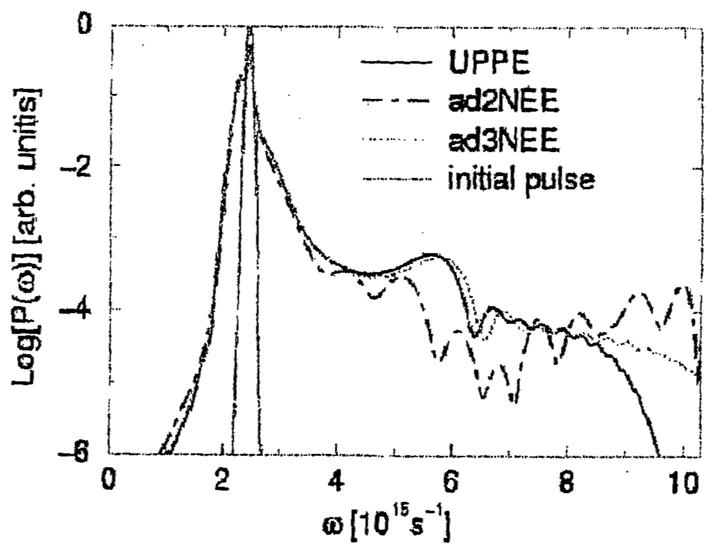



We have recently derived a general non-envelope propagation model that systematically includes linear and nonlinear propagation effects to all orders for a forward propagating pulse. The model fully resolves the optical carrier wave (as shown below) and allows for propagation of tens of centimetre to meter distances. It is fully vectorial in nature and contains the $\nabla \bullet \vec{E}$ vector coupling term ignored in scalar and most vector envelope models. This enables us to look at extreme linear/nonlinear focusing of ultrashort (femtosecond/attosecond) pulses down to wavelength scales in a material. The picture on the right shows that we can resolve the optical carrier wave accurately using about 8 points per wavelength. Time stepping is not restricted by the spatial propagation step – in fact the basic time interval is determined by the width of the z-window in the top picture. Therefore we can advance the solution over much larger steps than with Maxwell solvers. For example, the well-known FDTD method to solve Maxwell's equations in 1D, 2D and 3D requires 30-60 points per wavelength and the space step is linked to the time step by the Courant condition. Our unidirectional propagation approach is essentially a unidirectional vector Maxwell model. The problem is posed in the spectral representation making it convenient to input physical material dispersion (absorption/refraction) over many hundreds of nanometer bandwidths. This is particularly important for studying supercontinuum generation in gases and condensed media. The unidirectional pulse propagation equation (UPPE) evolves the electric displacement vector $\vec{D}$ rather than the electric field vector $\vec{E}$ in time.

$$\partial_t \vec{D}_f(\vec{k}) = -i\omega(k)\vec{D}_f(\vec{k}) + \frac{i}{2}\,\omega(k)\left[\vec{P}_{\rm NL}(\{\vec{D}\},\vec{k}) - \frac{1}{k^2}\vec{k}\;\vec{k}.\vec{P}_{\rm NL}(\{\vec{D}\},\vec{k})\right]$$

The first term on the write contains the exact linear dispersion of the material and can contain full absorption and transparency band material spectral features input from experimental measurements. Taylor series expansions of this term leads to all higher order dispersion and space-time derivative terms appearing in higher-order envelope equations.

The second term on the right contains a general nonlinear polarization term that is general enough to include nonlinear dispersive effects, various delayed nonlinear interactions etc. The last term on the right is the $\nabla \bullet \vec{E}$ term in Maxwell's equations. The above equation is formally exact and would be coupled to a corresponding backward field $\vec{D}_b$. By making the approximation $\vec{P}_{NL}(\vec{D}) = \vec{P}_{NL}(\vec{D}_f)$, we truncate the model by ignoring any backward generated field.




The picture on the right shows the supercontinuum for air calculated by the UPPE model (solid curve) and an envelope model truncated to include second order (dash-dot) and third order (dotted) dispersion. The location of the cut-off of the supercontinuum at short wavelengths (high frequencies) is a well-known feature of supercontinuum generation in various media and the truncated models fail to capture this. Appropriate truncations of our UPPE model lead to the usual extended NLS or to a recent model published in Physical Review Letters by Brabec et al. The UPPE is much broader in scope than this latter scalar model. It also provides a seamless and physically transparent transition to all other scalar and vector pulse propagation models in the literature. In particular we observe that, in studying supercontinuum generation, an inappropriate truncation of the exact propagation equations leads to artifacts in the computed spectrum. The UPPE equation has also been used to demonstrate that the accepted physical scenario for limiting the spectral bandwidth of the generated continuum is not valid. We have shown that chromatic dispersion is a major player.

We have also investigated the possibility that femtosecond duration laser pulses may more effectively penetrate through obscurants. Preliminary vector Maxwell simulations on the scattering of tightly focused pulses from a dielectric disk show evidence that a significant coherent component of the incident pulse propagates through the scatterer. Dynamic Mie scattering calculations support our numerical results in the linear scattering regime. Disk diameters ranging from 3 – 10 μm have been studied.

## Publications:

1. M. Mlejnek, M. Kolesik, J.V. Moloney and E.M. Wright, "Optically turbulent femtosecond light guide in air", Physical Review Letters, **83**, 2938 (1999).

2. J.V. Moloney, "Ultrafast Intense Probes of Nonlinear Optical Material Interactions," *Nonlinear Optical Materials* Workshop Proceedings, The IMA Volumes in Mathematics and its Applications, Springer-Verlag (101), pp. 177-204 (1999)

3. M. Kolesik, M. Mlejnek, J.V. Moloney and E.M. Wright, "Wide beam, high power femtosecond pulse propagation in air", SPIE Proceedings (2000).

4. J.V. Moloney, M. Kolesik, M. Mlejnek and E.M. Wright, "Femtosecond self-guided atmospheric light strings", Chaos, **10**, 559 (2000).

5. J. Schwarz, P. Rambo, J.-C. Diels, M. Kolesik, E.M. Wright and J.V. Moloney, "Ultraviolet filamentation in air", Opt. Commun., **180**, p383 (2000)

6. M. Mlejnek, M. Kolesik, E.M. Wright and J.V. Moloney, "Recurrent femtosecond pulse collapse in air due to plasma generation", Mathematics and Computers in Simulation, **56**, 563 (2001).

7. M. Kolesik, E.M. Wright and J.V. Moloney, "Polarization dynamics of femtosecond pulses propagating in air", Phys. Rev. E, **64**, p26607 (2001).

8. C.-C. Cheng, E.M. Wright and J.V. Moloney, Phys. Rev. Lett., "Generation of electromagnetic pulses from plasma channels induced by femtosecond light strings", **87**, p1 (2001).

9. J. Schojodt-Eriksen, J.V. Moloney, E.M. Wright, Q. Feng and P.L. Christiansen, "Polarization instability of femtosecond pulse-splitting in normally dispersive self-focusing media", Opt. Letts., **26**, p 78 (2001).

10. M. Kolesik and J.V. Moloney, "Unidirectional light propagation equation", submitted to Phys. Rev. Letts., (2002).